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Economics of size-structured forestry with carbon storage

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Abstract

We study the economics of carbon storage using a model that includes forest size structure and determines the choice between rotation forestry and continuous cover forestry. Optimal harvests may rely solely on thinning, implying infinite rotation and continuous cover forestry, or both thinning and clearcuts, implying finite rotation periods. Given several carbon prices and interest rates, we optimize the timing and intensity of thinnings along with the choice of management regime. In addition to the carbon storage in living trees, we include the carbon dynamics of dead trees and timber products. Forest growth is specified by an empirically validated transition matrix model for Norway spruce (*Picea abies* (L.) Karst.). The optimization problem is solved in its general dynamic form by applying bilevel optimization with gradient-based interior point methods and a genetic algorithm. Carbon pricing postpones thinnings, increases stand density by directing harvests to larger trees, and typically yields a regime shift from rotation forestry to continuous cover forestry. In continuous cover solutions, the steady-state harvesting interval and the diameter distribution of standing and harvested trees are sensitive to carbon price, implying that carbon pricing increases the sawlog ratio of timber yields. Additionally, we obtain relatively inexpensive stand-level marginal costs of carbon storage.

Keywords: carbon sequestration, carbon subsidy, continuous cover forestry, management regimes, optimal rotation, uneven-aged forestry

1. Introduction

Holding more than double the amount of carbon in the atmosphere, forest ecosystems are a crucial part of the global carbon cycle (FAO 2006). Carbon storage in forests can be maintained and increased by reducing deforestation, by afforestation and by changing stand-level forest management practices (IPCC 2014). While increasing forest cover may be challenging due to competing land uses (Lubowski et al. 2006), enhancing carbon storage per hectare of existing forestland may be a cost-efficient mitigation option. Our study analyses economically optimal carbon storage in size-structured stands of Norway spruce (*Picea abies* (L.) Karst.). Unlike previous studies, we apply a forest economic model that encompasses the two alternative forest management regimes: forest management based on clearcuts and management that maintains forest cover continuously. Using this generalized model, we present a detailed analysis of the effects of carbon storage on optimal management practices, including the choice between management regimes. The latter is vital given that climate change adaptation and biodiversity protection may motivate a more widespread application of continuous cover management (Gauthier et al. 2015).

In the boreal region and beyond, forestry has relied heavily on the rotation regime, where forest stands are artificially regenerated and finally clearcut, resulting in more or less even-aged stands (Gauthier et al. 2009). However, planted even-aged forests account for only 13% of managed forest area globally (FAO 2010, Payn et al. 2015). Further, recent research suggests that plantation forestry may be more vulnerable to disturbances related to climate change than forest management that maintains structurally diverse stands (Gauthier et al. 2015). An alternative to the rotation regime is continuous cover or uneven-aged forestry, where the stand is managed by partial cuttings (i.e. thinnings). Regeneration occurs naturally, resulting in a heterogeneous age and size distribution. In comparison to rotation forestry, continuous cover forestry is likely to support more biodiversity and other ecosystem services (Calladine et al. 2015, O'Hara 2014) and to be more resilient against threats brought about by climate change (Thompson et al. 2009).

While continuous cover forestry shows promise for climate change adaptation, cost-efficient mitigation measures have been analysed almost exclusively in the framework of rotation forestry. A seminal paper by van Kooten et al. (1995) examines the effect of carbon pricing on optimal rotation age and supply of carbon services. Akao (2011) shows how the effects of carbon storage on optimal rotation age depend on assumptions concerning the carbon release from wood products, while Hoel et al. (2014) extend the van Kooten et al. (1995) framework by including forests' multiple carbon pools, harvest residues and the use of timber for bioenergy. These along with numerous other studies apply the generic version of the Faustmann optimal rotation model, where stands can be harvested solely by clearcutting (Samuelson 1976). As commercial thinnings have an important role in e.g. Nordic context, they have been incorporated into even-aged models with carbon storage by e.g. Huang and Kronrad (2006), Pohjola and Valsta (2007) and Daigneault et al. (2010). Further, Niinimäki et al. (2013) for Norway spruce and Pihlainen et al. (2014) for Scots pine highlight the importance of adapting thinning strategies (in addition to the rotation period) for economically optimal carbon storage.

Studies on optimal carbon storage in continuous cover forestry are scarce, and most of the existing contributions have limited their scope to steady states (e.g. Buongiorno et al. 2012). Goetz et al. (2010) is an exception, as they dynamically optimize timber production and carbon storage in uneven-aged stands of Scots pine in Spain. The question of the relative profitability of rotation *vs.* continuous cover forestry in the co-production of timber and carbon storage has been touched upon in certain studies: Gutrich and Howarth (2007) compare management regimes with carbon storage, but do not optimize the regime choice, while Pukkala et al. (2011) analyse the choice of management regime applying a model without sound economic basis. As far as we know, no studies exist using a detailed dynamic model for analysing the effect of carbon storage on the choice between these two management regimes.

This gap is not surprising, as up to very recently, the economics of even- and uneven-aged forestry have been analysed separately and with divergent models. While the literature on even-aged forestry builds on Faustmann (1849), the first attempts to optimize uneven-aged management include de Liocourt (1898) and Adams and Ek (1974). As discussed in Getz and Haight (1989, p. 287–295) and Rämö and Tahvonen (2014), many studies have attempted to bypass the dynamic complexities involved in optimizing uneven-aged forestry. However, seminal contributions by Haight (1985) and Haight and Getz (1987) correctly specify the uneven-aged problem as an infinite time horizon problem without *ad hoc* restrictions. Recently it has been shown that when the optimal choice between continuous cover *vs*. rotation forestry is determined endogenously, both management regimes can be analysed using the same model (Tahvonen and Rämö 2016). This generalized approach allows for the optimization of stand management – thinnings and the (potentially infinite) rotation age – over an infinite time horizon given any initial state. The study at hand extends this model by including the social value of carbon storage.

Our present study is the first one to apply an empirically validated size-structured growth model to the problem of optimal carbon storage with endogenous choice of management regime. Our study features a detailed economic setup with empirically estimated variable harvesting cost functions, along with fixed harvesting costs that necessitate the optimization of thinning intervals. This not only allows us to obtain the first results on optimal harvest timing in uneven-aged forestry with carbon storage, but is also essential for accurately determining the relative economic performance of the rotation and continuous cover regimes. The effect of carbon storage on the optimal choice between these regimes is a question with major practical implications, but one that has not been satisfactorily studied in the previous literature. Our carbon storage formulation explicitly includes carbon dynamics in the whole tree biomass, in dead tree matter and in timber products with distinct decay rates for sawlog and pulpwood products. By combining detailed economic and ecological models, and by optimizing not only rotation age but thinnings and the management regime as well, we are able to determine the most cost-efficient methods for enhancing carbon storage in managed forests.

We continue by introducing the growth model and the optimization problem. Thereafter we present the empirical parameter values and the computational methods. This is followed by results on optimal stand management, on timber production and carbon storage, and on forestry revenues and carbon storage costs. Finally, we discuss our results by comparing them with earlier studies and draw conclusions.

2. The growth model and the optimization problem

We denote the number of trees in size class *s* at the beginning of period *t* by $x_{st},\ s=1,2,...,n,\ t=t_1,t_1+1,...,T+1$. Accordingly, the stand state at period *t* can be given as $\mathbf{x}_t=\left[x_{1t},x_{2t},\ldots,x_{nt}\right]$. Let us denote the fraction of trees moving to size class $s+1$ at period *t* by $\beta_s\left(\mathbf{x}_t\right),\ s=1,2,...,n$, where $\beta_n\left(\mathbf{x}_t\right)\equiv 0$. The natural mortality in size class *s* at period *t* is $\mu_s\left(\mathbf{x}_t\right),\ s=1,2,...,n$. Thus the fraction of trees remaining in the same size class equals $1-\beta_s\left(\mathbf{x}_t\right)-\mu_s\left(\mathbf{x}_t\right),\ s=1,2,...,n$. Natural regeneration is described by ingrowth, i.e. trees entering the smallest size class. Ingrowth at the beginning of period *t* is denoted by $\phi\left(\mathbf{x}_t\right)$. Additionally, we denote the number of trees harvested from size class *s* at the end of period *t* by $h_{st},\ s=1,2,...,n,\ t=t_1,t_1+1,..,T$. Hence, stand development can be described by the difference equations

(1) $$x_{1,t+1}=\phi\left(\mathbf{x}_t\right)+\left[1-\beta_1\left(\mathbf{x}_t\right)-\mu_1\left(\mathbf{x}_t\right)\right]x_{1t}-h_{1t},$$

(2) $$x_{s+1,t+1}=\beta_s\left(\mathbf{x}_t\right)x_{st}+\left[1-\beta_{s+1}\left(\mathbf{x}_t\right)-\mu_{s+1}\left(\mathbf{x}_t\right)\right]x_{s+1,t}-h_{s+1,t},\ s=1,2,...,\mathrm{n}-2,$$

(3) $$x_{n,t+1}=\beta_{n-1}\left(\mathbf{x}_t\right)x_{n-1,t}+\left[1-\mu_n\left(\mathbf{x}_t\right)\right]x_{nt}-h_{nt},$$

where $t=t_1,t_1+1,...,T$.

We assume that the stand is artificially regenerated after a clearcut, and the time interval between the regeneration activities and the ingrowth of trees into the smallest size class equals a certain number of periods denoted by t_1. Thus, t_1 periods after planting, we have an initial stand composed of a given number of trees in size class 1. The stand is clearcut if the rotation length $T \in [t_1, \infty)$ is finite.

Let $w \geq 0$ (€ ha^{-1}) denote the cost of artificial regeneration. We denote the discount factor by $b = 1/(1+r)$, where *r* refers to the annual interest rate. The length (in years) of a period is denoted by Δ. Revenues, $R(\mathbf{h}_t)$ from thinning and $R(\mathbf{x}_T)$ from clearcuts, depend on the number and size of trees harvested. The revenues per period are specified as

(4) $$R(\mathbf{h}_t) = \sum_{s=1}^{n} h_{st} \left(v_{\sigma,s} p_\sigma + v_{\varpi,s} p_\varpi \right), t = t_1, t_1 + 1, \ldots T,$$

where $v_{\sigma,s}$ and $v_{\varpi,s}$ are the sawlog and pulpwood volumes in a tree of size class *s*, and p_σ and p_ϖ are the respective (roadside) prices (€ m^{-3}). Variable harvesting costs (for cutting and hauling) are given separately for thinning and clearcuts by $C_i(\mathbf{h}_t),\ i = th, cl$. A fixed harvesting cost denoted by C_f covers e.g. the transportation of machinery to the stand site. Because of the fixed cost it may not be optimal to harvest the stand in every period. This is taken into account by the binary variables $\delta_t \in \{0,1\},\ t = t_1, t_1 + 1, \ldots, T$ and by the Boolean operator $h_t = \delta_t h_t$. When the choice is $\delta_t = 1,$ the levels of $h_{st} \geq 0,\ s = 1, 2, \ldots, n$ can be freely optimized. When $\delta_t = 0$, the only admissible choice is $h_{st} = 0,\ s = 1, 2, \ldots, n.$

As carbon storage in forests is a positive externality, we assume a Pigouvian subsidy system resembling the one in van Kooten et al. (1995). Accordingly, society pays the forest owner for the amount of CO_2 that is absorbed as the stand grows, and charges for the amount of CO_2 that is released as a consequence of harvesting and natural mortality. Let $p_c \geq 0$ (€ tCO_2^{-1}) denote the economic value of CO_2. We let $\omega_t = \sum_{s=1}^{n} x_{s,t}\left(v_{\sigma,s} + v_{\varpi,s}\right)$ denote the merchantable timber volume (i.e. stem volume) of the stand at the beginning of period *t*. Density factor ρ converts stem volume into stem dry mass. In addition to the stem, trees are comprised of non-merchantable matter, i.e. foliage, branches, bark, stumps and roots. Expansion factor η converts stem dry mass into whole tree dry mass. Hence, the total tree biomass in the stand at the beginning of period *t* can be given as $B_t\left(\mathbf{x}_t\right) = \rho\eta\omega_t$, and net biomass growth in period t as $B_{t+1}\left(\mathbf{x}_{t+1}\right) - B_t\left(\mathbf{x}_t\right)$. The amount of CO_2 in one dry mass unit equals θ.

We denote the dry mass of sawlog and pulpwood harvested at the end of period *t* by $y_{\sigma,t} = \rho\sum_{s=1}^{n} h_{st}\, v_{\sigma,s}$ and $y_{\varpi,t} = \rho\sum_{s=1}^{n} h_{st}\, v_{\varpi,s}$, respectively. Logging will not instantly release the carbon content of timber into the atmosphere because it is only gradually released from timber products as they decay (Liski et al. 2001). Dead tree matter is created both through natural mortality and from harvest residues (i.e. non-merchantable parts of the harvested trees) left in the forest. The dry mass of dead tree matter formed through natural mortality in period *t* equals $d_{m,t} = \rho\eta\sum_{s=1}^{n} \mu\left(\mathbf{x}_t\right)_{s,t} x_{s,t}\left(v_{\sigma,s} + v_{\varpi,s}\right)$. Further, the dry mass of harvest residues created at the end of period *t* can be given as $d_{h,t} = (\eta - 1)\left(y_{\sigma,t} + y_{\varpi,t}\right)$. We denote the annual decay rates of sawlog, pulpwood and dead tree matter, respectively, by g_j ($j = \sigma, \varpi, d$). The urgency of mitigating climate change implies that society is likely to have a positive time preference for net emissions. It can be shown that, per unit of wood product or dead tree matter, the present value of future emissions due to decay equals $p_c\, \alpha_j\left(r\right)$, where

(5) $$\alpha_j\left(r\right) = \frac{g_j}{g_j + r}$$

(cf. Pihlainen et al. 2014, Assmuth and Tahvonen 2017).

Thus the economic value of net carbon sequestration (or net negative emissions) in period *t* can be given as

(6) $$Q_t = p_c\theta\left\{B_{t+1}\left(\mathbf{x}_{t+1}\right)-B_t\left(\mathbf{x}_t\right)+\left[1-\alpha_\sigma\left(r\right)\right]y_{\sigma,t}\left(\mathbf{h}_t\right)+\left[1-\alpha_\varpi\left(r\right)\right]y_{\varpi,t}\left(\mathbf{h}_t\right)+\left[1-\alpha_d\left(r\right)\right]\left(d_{m,t}\left(\mathbf{x}_t\right)+d_{h,t}\left(\mathbf{h}_t\right)\right)\right\}$$

for $t = t_1, t_1+1, ..., T$,

where $B_{t+1}\left(\mathbf{x}_{t+1}\right)-B_t\left(\mathbf{x}_t\right)$ refers to net growth, i.e. the change in biomass net of harvests. The additional elements $\left[1-\alpha_\sigma\left(r\right)\right]y_{\sigma,t}\left(\mathbf{h}_t\right)$ and $\left[1-\alpha_\varpi\left(r\right)\right]y_{\varpi,t}\left(\mathbf{h}_t\right)$ are needed to take into account that harvested trees are used for sawlog and pulpwood products, respectively, which release their carbon content as they decay. Correspondingly, $\left[1-\alpha_d\left(r\right)\right]\left(d_{m,t}\left(\mathbf{x}_t\right)+d_{h,t}\left(\mathbf{h}_t\right)\right)$ refers to dead tree matter (from natural mortality and harvest residue) and its decay.

The problem of optimizing harvests over an infinite horizon can now be given as

(7) $$J\left(\mathbf{x}_0,T\right)=\max_{\left\{h_{st},\delta_t,T\in\left[t_1,\infty\right)\right\}}\frac{-w+\sum_{t=0}^{T}Q\left(\mathbf{x}_t,\mathbf{h}_t\right)b^{\Delta(t+1)}+\sum_{t=t_1}^{T}\left[R\left(\mathbf{h}_t\right)-C_i\left(\mathbf{h}_t\right)-\delta_t C_f\right]b^{\Delta(t+1)}}{1-b^{\Delta(T+1)}}$$

s.t. (1) – (3) and

(8) $$\delta_t \in \{0,1\},\ t = t_1, t_1+1, ..., T$$

(9) $$x_{st} \geq 0,\ s = 1,2,...,n,\ t = t_1, t_1+1, ..., T+1,$$

(10) $$h_{st} = \delta_t h_{st} \geq 0,\ s = 1,2,...,n,\ t = t_1, t_1+1, ..., T,$$

(11) $$\mathbf{x}_{T+1} = 0,$$

(12) x_{s,t_1} given.

The optimal forest management regime is determined by the choice of *T*. If – given optimized thinnings – the objective functional is maximized by a finite rotation age, rotation forestry is optimal. If no maximum exists and the bare land value converges toward the continuous cover forestry bare land value from below as $T \rightarrow \infty$, then it is optimal to apply continuous cover management.

3. Ecological and economic parameter values

We apply an empirical growth model by Bollandsås et al. (2008) for Norway spruce at latitude 61.9 ºN. The model has been estimated using the National Forest Inventory of Norway, and includes functions for ingrowth, mortality and diameter increment. We study an average productivity site ($SI = 15$), implying that the height of the dominant trees at the age of 40 (100) years is 15 (24) metres. We use 12 size classes with diameters (midpoints) ranging from 7.5 cm to 62.5 cm with 5.0 cm intervals. Table 1 presents the size class -specific parameter values (Rämö and Tahvonen 2014). The length of a period (Δ) is five years and the time interval from planting to the emergence of trees into the first size class is 20 years (i.e. $t_1 = 4$). The initial stand structure is given as $\mathbf{x}$ = [2250, 0, 0, …], i.e. 20 years after artificial regeneration, 2250 trees emerge in the smallest size class.

The estimated natural mortality during the 5-year period *t* in size class *s* is given as

$\mu_{st} = \left(1 + e^{-\left(-2.492 - 0.020 M_s + 3.2 \cdot 10^{-5} M_s{}^2 + 0.031 A_t\right)}\right)^{-1}$, where M_s is the diameter (midpoint) of size class *s* and A_t the total stand basal area (m² ha⁻¹) at the beginning of period *t*. The fraction of trees moving to the next size class during period *t* is denoted by

$$\beta_{st} = \left(1.2498 + 0.0476 M_s - 11.585 \cdot 10^{-5} M_s{}^2 - 0.3412 L_{st} + 0.906 \cdot SI - 0.024 A_t\right) / 50,$$

where L_{st} is the total basal area of size classes $s+1,...,n$ at the beginning of period *t*. The estimated number of trees entering the smallest size class (i.e. natural regeneration) during the 5-year period *t* is given as $\phi_t = \dfrac{54.563\left(A_t + a\right)^{-0.157} \cdot SI^{0.368}}{1 + e^{\left(0.391 + 0.018 A_t - 0.066 \cdot SI\right)}}$.

Note that ϕ is strictly convex in $\mathbf{x}$, implying nonconvexities in the optimization problem. In Bollandsås et al. (2008), $a = 0$ and $\phi \to \infty$ as $\mathbf{x} \to 0$. This feature is unwarranted, and based on Wikberg (2004) and Pukkala et al. (2009) we set $a = 0.741$, which implies $\phi(0) = 100$. This correction parameter decreases the ingrowth by less than one tree per year when basal area is above 2 m^2.

The roadside prices for sawtimber and pulpwood are €58.44 m^{-3} and €34.07 m^{-3}, respectively. The fixed harvesting cost equals €500 ha^{-1}. For the variable harvesting costs we use empirically estimated functions by Nurminen et al. (2006), based on the performance of modern harvesters. The variable harvesting costs (cutting and hauling) depend on the number and volumes of trees cut, and are given separately for thinning and clearcuts as

$$C_i = C_{i0} C_{i1} \sum_{s=1}^{n} h_{st} \left(C_{i2} + C_{i3} v_s - C_{i4} v_s^{2} \right) + C_{i5} \left[C_{i6} \sum_{s=1}^{n} h_{st} v_s + C_{i7} \left(\sum_{s=1}^{n} h_{st} v_s \right)^{0.7} \right], \, i = th, cl.$$

C_{i0} is the per-minute cutting cost (€), and its coefficient $C_{i1}\left(\bullet\right)$ is the time (in minutes) spent cutting one tree and moving the machinery to the next tree. C_{i5} and its coefficient $\left[\bullet\right]$ are the cost and time spent in hauling, respectively, while $v_s = v_{\sigma,s} + v_{\varpi,s}$ is the volume of a tree in size class *s*. The parameter values for $C_{ik}, i = th, cl, k = 0,...,7$ are given in Table 2. The parameter $C_{th1} = 1.150$ in the cutting cost element for thinning takes into account that cutting one tree and moving to the next one is more costly in (continuous cover) thinning compared to clearcuts (Surakka and Siren 2007). Additionally, hauling is more time-consuming in thinnings than in clearcuts. The cost of artificial regeneration is €1000–1500 ha^{-1} (Niinimäki et al. 2012). We apply the lower bound because this will reveal how carbon storage alters the choice between continuous cover and rotation forestry.

Based on Lehtonen et al. (2004), the stemwood density factor (ρ) for Norway spruce is 0.3774 tonnes of dry matter per cubic metre of fresh volume, and the expansion factor to convert stem dry mass into whole tree dry mass (η) equals 2.1566. Following Niinimäki et al. 2013, the CO_2 content of a wood dry mass unit (θ) is obtained by multiplying the share of carbon in biomass dry weight (0.5) with the coefficient that converts tonnes of carbon to tonnes of CO_2 (44/12). Thus we set $\theta = 1.83333$ $tCO_2\,t^{-1}$. For the decay rate of dead tree matter we use $g_d = 0.18196$ based on the average rate of stem, foliage, branches, bark, stumps and roots in Hyvönen and Ågren (2001). To obtain the decay rates for sawlog and pulpwood products we use data presented in Liski et al. (2001) on the division of sawlog and pulpwood removals for production lines, on production losses, and on the division into timber product types with different lifespans. The obtained parameter values are $g_{\sigma} =$ 0.06611 and $g_{\varpi} = 0.47070$.

4. Computational methods

Because the harvest timing variables are integers, but harvest intensities are continuous, the task is to solve a mixed-integer nonlinear programming problem. To do this, we apply bilevel optimization (Colson et al. 2007).[1] The lower-level problem is computed using version 9.0 of the Knitro optimization software, which applies advanced gradient-based interior point algorithms (Byrd et al. 2006). The maximized objective value of the lower-level problem forms the objective value given any vector of harvest timing binaries. The harvest timing vector is optimized using a genetic algorithm (Deb and Sinha 2010, Sinha et al. 2017). The optimal harvest schedules are solved for a series of rotation lengths. If the objective function obtains a maximum with some $T \in [60,180)$ years, the optimal rotation is finite. If the value of the objective function continues to increase as the rotation period is lengthened, the optimal rotation is infinite. In this case, the optimal continuous cover solution is obtained by lengthening the horizon to obtain a close approximation of the infinite horizon solution. To handle potential non-convexities, we apply multiple randomly chosen initial points in the optimization. For the genetic algorithm, we use a randomly generated initial population of 40 harvest timing vectors, and for each harvest intensity optimization we use four random initial points. These values were found to be sufficient for finding the same local optimum as a higher number of initial guesses. Using efficient parallel computation (Intel (R) Xeon (R)E5-2643 v3 @3.40GHZ, 24

[1] A similar approach has been applied to a forest management problem without carbon storage in Tahvonen and Rämö (2016).

logical processors), the optimal harvest intensity and timing is found within 3–36 h. The solution times for the lower lever problem are typically 5–15 seconds with approximately 20% variability in the objective values of the local optima based on different initial points.

5. Results

The effects of carbon pricing on optimal stand management

For reference, we first briefly state results for the generic Faustmann setting (Samuelson 1976), where harvesting can be carried out solely in clearcuts (i.e. no thinnings), and no natural regeneration takes place. This setting is similar to that of the carbon storage study by van Kooten et al. (1995). Given an annual interest rate of 2%, with zero carbon price, the optimal rotation age is 60 years. Setting a carbon price of €20 (€30) tCO_2^{-1} lengthens the optimal rotation period to 65 (70) years, while a carbon price of €60 tCO_2^{-1} implies a 90-year rotation period. Given a 4% annual interest rate, the effect of carbon pricing on rotation length is somewhat stronger. Increasing the carbon price from zero to €60 tCO_2^{-1} increases the optimal rotation age from 50 years to 110 years.

We now turn to the full economic setup with optimized intensity and timing of thinnings along with an optimized rotation period and management regime. Given a 2% annual interest rate, optimal rotation age increases with carbon price (Table 3, Figure 1). The optimal rotation length without carbon pricing equals 130 years. The relatively long rotation follows from optimally utilizing natural regeneration. When carbon price equals €10 (€20) tCO_2^{-1}, the rotation age is 150 (170) years. Given a carbon price of €30 tCO_2^{-1} or higher, the optimal rotation period is infinitely long, implying that continuous cover forestry is superior to rotation forestry. Given a 4% interest rate, the optimal rotation is infinite even with zero carbon price (Table 3, Figure 2). This is because a high interest rate makes it optimal to postpone or avoid the investment in artificial regeneration, as natural regeneration maintains a sufficient level of growth without costs. Moreover, a higher interest implies lower optimal stocking and thus a smaller opportunity cost of delaying the clearcut. Additionally, the time delay between stand regeneration and the first revenues from thinnings becomes costly when discounting is heavier. This encourages a shift to continuous cover forestry with more frequently repeated harvests.

Regardless of management regime (rotation forestry or continuous cover forestry), optimal thinning is invariably performed from above, always fully cutting down the largest harvested size class. Relative value growth is very high in small trees, implying that it is optimal to postpone harvesting until they have grown to a size that yields sawlog. Given a 2% interest rate and zero carbon price, the first thinning takes place 45 years after stand regeneration (Table 3, Figure 1). Carbon pricing postpones the first thinning by five years, and increases mean stand volume along the rotation – or, in the case of continuous cover solutions, at the steady state (Table 3). The timing and intensity of subsequent thinnings can be seen in Figure 1, where stand volume and the number of trees drop after each harvest. Given a 4% interest rate and no carbon pricing, the first thinning is carried out already at a stand age of 40 years (Table 3, Figure 2), as it is optimal to maintain less capital in the stand. A carbon price of €20 (€60) tCO_2^{-1} postpones the first thinning by five (15) years.

The relative effect of carbon pricing on optimal stand management and stand density is larger with a higher interest rate. Given a 2% interest rate, mean stand volumes range from 138 to 224 m^3 ha^{-1} for carbon prices €0–€60 tCO_2^{-1}; given a 4% interest rate the corresponding mean stand volumes span from 68 to 234 m^3 ha^{-1} (Table 3). From the economic point of view, forest carbon storage essentially means shifting net emissions forward in time. Thus stronger discounting implies a stronger incentive to adapt forest management to provide more carbon storage.

The higher the carbon price, the larger the harvested trees at the continuous cover steady states (Table 3, Figure 3). Additionally, the number of size classes harvested equals the number of five-year periods between the steady-state harvests. Given a 2% interest rate and a carbon price of €30 tCO_2^{-1}, trees are harvested from five size classes in the optimal continuous cover solution (diameter midpoints

32.5, 37.5, 42.5, 47.5 and 52.5 cm) with a 25-year interval. When carbon price increases to €60 tCO_2^{-1}, it is optimal to forgo harvesting the 32.5 cm diameter class and to only cut trees with diameters of 37.5–52.5 cm. This is achieved by switching to a 20-year harvesting interval (Table 3). Thus harvest timing adjusts to the carbon price to maintain optimal average stand density and economic return (including carbon subsidies) along the harvest interval.

Given a 4% interest rate and zero carbon price, the steady-state harvest takes place every 20 years, and targets trees with diameters of 22.5–37.5 cm (Table 3, Figure 3). With a €10 tCO_2^{-1} carbon price, the steady-state harvesting interval equals 25 years, allowing some trees to enter the 42.5 cm size class before they are harvested. Increasing the carbon price further shifts the steady-state harvests to larger size classes, implying a higher mean stand volume. While the number of trees decreases with tree size class (Figure 3, column a), large trees comprise a considerable fraction of the total stem volume because of their high volume per tree (Figure 3, column b).

The effects of carbon pricing on timber production and carbon storage

Given a 2% interest rate and zero carbon price, mean annual sawlog yield over the rotation equals 6.3 m^3 ha^{-1}, while mean annual total yield (sum of sawlog and pulpwood) equals 7.6 m^3 ha^{-1} (Table 4). Increasing the carbon price to €10 (€20) tCO_2^{-1} increases mean sawlog yield to 6.5 (6.7) m^3 ha^{-1} while total yield remains unchanged, i.e. the sawlog-pulp ratio increases. This has a positive effect on carbon storage because the typical decay rate of sawlog products is notably slower than that of pulpwood. Increasing the carbon price to €30 tCO_2^{-1} implies a regime shift from rotation forestry to continuous cover forestry, and decreases mean sawlog and total yield while increasing the sawlog ratio. The explanation is that continuous cover management tends to produce somewhat lower mean yields than rotation forestry, even when the bare land value of the former is higher. Increasing the carbon price further, to €60 tCO_2^{-1}, has only a negligible effect on mean sawlog and total yields.

Given a 4% interest rate and no carbon pricing, mean sawlog and total yields are low, 3.8 and 4.5 m^3 ha^{-1} a^{-1}, respectively (Table 4). This is due to the low optimal level of growing capital. With carbon pricing, trees are allowed to grow bigger before they are harvested (Table 3), which increases yields when the carbon price is relatively low. For example, given a carbon price of €30 tCO_2^{-1}, the mean sawlog yield equals 5.7 m^3 ha^{-1} and mean total yield is 6.7 m^3 ha^{-1}. However, with €60 tCO_2^{-1} carbon price, mean sawlog and total yields equal 5.6 and 5.8 m^3 ha^{-1}, respectively (Table 4). This implies that when the carbon price is sufficiently high, yields begin to decrease with carbon price because only very large trees are harvested.

Natural mortality remains rather low in economically optimal solutions, but dead tree matter is generated from harvest residues. Each harvest decreases the carbon storage in living trees, but causes a temporary increase in carbon storage in dead tree matter and in timber products (Figure 4). The latter two, however, quickly decrease as a consequence of decay. This is especially true for clearcuts (Figure 4a–c), which yield large amounts of rapidly decaying pulpwood. Because of exponential decay, the initial carbon stocks in dead tree matter and in timber products reach a steady state, where total carbon storage at the beginning of the rotation equals total carbon storage at the end of the rotation. In continuous cover solutions (Figure 4d), carbon stocks in living trees, dead tree matter and timber products go through a transition phase before reaching a steady state.

Mean carbon storage in living trees increases with carbon price (Table 4). For example, given a 2% interest rate and no carbon pricing, the average amount of carbon stored in living trees over a rotation is 207 tCO_2 ha^{-1}; increasing the carbon price to €60 tCO_2^{-1} increases mean storage to 335 tCO_2 ha^{-1}. Additionally, mean carbon storage in dead tree matter and timber products generally increase with carbon price. An exception is the regime shift from rotation forestry to continuous cover forestry (2% interest rate, carbon price from €20 to €30 tCO_2^{-1}). As mentioned, rotation forestry produces high total yields and thus large amounts of harvest residues, and average natural mortality is somewhat higher in rotation forestry than in continuous cover forestry. Moreover, the calculation of mean carbon storage in dead tree matter and timber products takes into account the accumulation of these stocks from one rotation to the next.

In solutions where continuous cover management is optimal, the steady state may be reached as late as approximately 300 years after stand regeneration. This implies that in terms of economic outcome, the carbon storage taking place during the long transition phase towards the steady state is likely to be more important than mean carbon storage. Discounted CO_2 sequestration (tCO_2 ha^{-1}) is the sum of all periodic net carbon fluxes within the infinite planning horizon, each discounted to the present (stand regeneration) moment. For example, given a 2% interest rate and a carbon price of €20 tCO_2^{-1}, the net carbon sequestration over the infinite horizon is equivalent to 232 tonnes of CO_2 emissions abated immediately. Discounted CO_2 sequestration increases monotonously with carbon price (Table 4).

Forestry revenues and the cost of carbon storage

The higher the carbon price, the lower the discounted timber income (Table 5). This is true despite of the fact that the mean timber yields do not monotonically decrease with carbon price (Table 4). The decrease in discounted timber income is partly explained by differences in harvest timing: when carbon storage is valued, harvests are carried out later. Additionally, deviating from the optimal timber-only solution implies higher harvesting costs per timber unit. However, the decrease in timber income is more than compensated by carbon subsidies that represent the economic value of carbon storage. Including carbon storage benefits improves net present values (i.e. bare land value) considerably: given a 2% (4%) interest rate, a carbon price of €20 tCO_2^{-1} increases net present value by 50% (137%) (Table 5). If the social value of carbon storage is high (€30 or €60 tCO_2^{-1} depending on interest rate), the economic benefits from carbon storage clearly overweigh the income from timber production.

The economic cost of additional carbon storage, i.e. the cost of carbon abatement in forestry, is measured as lost timber income. To obtain marginal abatement costs, we divide the incremental decrease (i.e. from the solution with a lower carbon price) in timber income for each optimal solution by the corresponding incremental increase in discounted CO_2 sequestration.[2] Marginal abatement costs increase with the amount of carbon abatement (Figure 5). Given a 2% interest rate, marginal costs range from €3 to €46 tCO_2^{-1} for 10 to 70 tonnes of carbon abatement per hectare. Given a 4% interest rate abatement is somewhat more costly, but carbon abatement up to 33 tonnes per hectare can be achieved with a marginal cost below €40 tCO_2^{-1}.

6. Discussion and conclusions

It is widely established in the literature that valuing carbon storage increases optimal rotation age in even-aged forestry (e.g. van Kooten et al. 1995, Stainback and Alavalapati 2002, Gutrich and Howarth 2007, Pohjola and Valsta 2007). While our findings support this result, our model differs from previously published models in many important aspects and is able to shed light on previously unaddressed questions. Unlike many studies, we include thinnings, and optimize their timing along with their intensity. Further, we determine the optimal management regime – rotation forestry or continuous cover forestry – endogenously. As far as we know, such an optimization approach has not been combined with carbon storage using a size-structured description of forest resources.

Including thinnings (and natural regeneration) is essential for our approach, because it implies that timber revenues may be obtained from a forest that is never clearcut. This is not the case in studies applying the classic Faustmann rotation model, e.g. van Kooten et al. (1995) and Hoel et al. (2014). van Kooten et al. (1995) find that carbon pricing generally increases rotation ages only moderately, but in certain cases might yield a result where it is optimal to forgo harvesting completely. Hoel et al. (2014) show that rotation age typically increases with the social cost of carbon and may become infinitely long (i.e. forestry is abandoned). According to our results, carbon pricing may indeed render the optimal rotation infinitely long, but instead of total abandonment of harvesting as

[2] Note that an amount of discounted CO_2 sequestration corresponds to an equal amount of emissions abated immediately.

in van Kooten et al. (1995) and Hoel et al. (2014), it then becomes optimal to manage the stand with thinnings (i.e. apply continuous cover forestry).

According to studies that included optimized thinnings in their even-aged setup (e.g. Pohjola and Valsta 2007, Daigneault et al. 2010, Niinimäki et al. 2013), carbon pricing tends to postpone thinnings, increase mean stand volume and lengthen the optimal rotation period. Our results support these findings. However, our generalized model yields optimal solutions that go beyond the scope of earlier studies limited to forests without natural regeneration. Given the low interest rate (2%), optimal rotations are long, ranging from 130 to 170 years for carbon prices €0–€20 tCO_2^{-1}. With a €30 tCO_2^{-1} carbon price, clearcutting is suboptimal, i.e. the optimal management regime switches from rotation forestry to continuous cover forestry. Given a higher interest rate (4%), continuous cover forestry dominates rotation forestry regardless of carbon price[3], and management adapts to carbon pricing by changing the timing and targeting of thinnings.

In our model setup, it is possible to exclude natural regeneration by setting $\phi(\mathbf{x}_t)=0$ in Eq. 1 (implying that any naturally regenerated saplings are cleared away, and the clearing is costless). If this is done, we obtain optimal rotation ages that are well in line with those obtained in earlier studies on even-aged Norway spruce: the study by Solberg and Haight (1991) based on a size-structured growth model, and the study by Niinimäki et al. (2013) utilizing a highly detailed process-based model. Without natural regeneration and given a 2% interest rate, our optimal rotation lengths range from 100 to 155 years for carbon prices €0–€60 tCO_2^{-1}. Given a 4% interest rate, rotation periods for carbon prices €0–€30 tCO_2^{-1} span from 100 to 130 years, while a carbon price of €60 tCO_2^{-1} yields an optimal rotation as long as 215 years.

With the exception of Goetz et al. (2010), studies on uneven-aged management with carbon storage tend to apply static optimization, which does not allow optimizing stand transition from any

[3] This is in line with Tahvonen and Rämö (2016), where high site productivity, low interest rate and low regeneration cost favour the clearcut regime instead of continuous cover regime, and *vice versa*.

initial state that is not close to the steady state (e.g. Pukkala et al. 2011, Buongiorno et al. 2012). Further, as far as we know, our study presents the first results on optimal harvest timing in uneven-aged forestry with carbon storage. Our results suggest that when beginning with bare land, the large initial cohorts are intensively utilized in a series of thinnings before approaching the steady state, and that these thinnings are postponed and moderated by carbon pricing. Reaching the steady state may take as much as 300 years from stand regeneration, which emphasizes the importance of the transition phase for the present value of net revenues from both timber production and carbon storage. We also show that the steady-state harvesting interval, along with the diameter distribution of the standing and harvested trees, react to changes in carbon price. The average size of the harvested trees increases with carbon price, and four (or five) diameter classes are fully harvested each 20 (25) years at the steady state.

The carbon storage formulation presented in van Kooten et al. (1995) takes into account that while carbon is stored in living trees, it may also be stored to some extent in timber products. We add detail to this formulation by explicitly including carbon storage in timber products and in dead tree matter. Our results suggest that a small carbon stock is maintained in dead tree matter, formed from harvest residues and through natural mortality. To account for carbon storage in timber products, we use distinct decay rates for sawlog and pulpwood (cf. Pihlainen et al. 2014). This is important because our size-structured model enables us to direct thinnings to trees of specific size, making use of the fact that large trees yield relatively more sawlog than small trees. Sawlog, in turn, is superior to pulpwood in its ability to store carbon for extended periods. Such targeted harvesting is by definition impossible in clearcuts, which inevitably results in the harvesting of quickly decaying pulpwood. This becomes costly with a high carbon price. Hence the impact of carbon storage on the relative profitability of rotation forestry *vs*. continuous cover forestry cannot be fully captured by a model that omits the size structure of the stand, or the varying decay profiles of timber assortments. According to our results, carbon pricing indeed increases the sawlog-pulp ratio of the mean annual yield and may induce a regime shift to continuous cover forestry.

The model developed in this study is a stand-level model, and thus does not include market interactions. However, our results yield some initial understanding on the effects of carbon storage on wood supply. In general, carbon pricing increases mean total annual yields, mostly due to increased sawlog production. The only exception to this is the case with a low interest rate (2%), where a carbon price of €30 tCO_2^{-1} induces a shift from rotation forestry to continuous cover management with somewhat lower mean yields. Given an interest rate equal or above 4%, continuous cover management with fairly low stand density is optimal when carbon storage is not valued, and carbon pricing clearly increases stocking levels along with the yields.

The cost of artificial regeneration has a large effect on the relative profitability of continuous cover and rotation forestry (Tahvonen and Rämö 2016). In this study, we have assumed the cost of artificial regeneration to be €1000 ha^{-1}, which is on the lower side of the typical cost range in Finland. If the regeneration cost is set higher, e.g. €2000, continuous cover management is optimal regardless of carbon price even with low interest rates. Low site productivity has a similar effect.

McKinsey & Company (2009) estimates a global abatement potential of almost 8000 $MtCO_2$ per year in the forestry sector for a marginal cost range from €2 to €28 tCO_2^{-1}. In van Kooten et al. (2009), a meta-regression analysis of forest carbon storage costs is performed using 1047 observations from 68 studies. Depending on the regression model used, the authors obtain highly varying estimates on the marginal costs of carbon storage. According to van Kooten et al. (2009), storage costs are higher in the boreal region than in the tropics or than the global average. Within the boreal region, their estimates are roughly equal to €4–€94 tCO_2^{-1} for plantation activities and 34–€155 tCO_2^{-1} for adaptation of forest management. However, Niinimäki et al. (2013) show that optimizing the stand management of Norway spruce yields additional discounted carbon storage up to 40 tCO_2 ha^{-1} with marginal costs in the range of €6–€36 tCO_2^{-1}.[4] Our results, obtained using a stand-level model with optimized management regime choice, point to a cost range of €5–€47 tCO_2^{-1} with as much as 70 tCO_2 ha^{-1} of abatement potential. This suggests that if all relevant aspects of forest management adaptation are optimized, increasing carbon storage can be relatively inexpensive even in the boreal region.

In 2015 the European Union (EU) committed to reducing its domestic greenhouse gas emissions by at least 40% from the 1990 level by 2030 (European Commission 2015). According to an impact assessment by the Commission, fulfilling this commitment would imply a carbon price in the range of €11–€53 tCO_2^{-1} (depending on policy scenario) in the EU Emissions Trading Scheme (ETS) by 2030. The range of projected prices in 2050 is €85–€264 tCO_2^{-1} (European Commission 2014, p. 80–81.) Such carbon price levels would incentivize major changes in forest management, if carbon storage in forests was linked to the ETS. Currently, however, New Zealand is the only country that has integrated forest carbon storage in its emissions trading system (Adams and Turner 2012). Whether or not similar approaches will be adopted in the EU and elsewhere, forest carbon storage is likely to play an important role in any cost-effective climate change abatement strategy.

We have presented a way to study economically optimal carbon storage in forestry without limiting the analysis to either even-aged or uneven-aged forestry. By determining the optimal management regime endogenously, we can cover both regimes simultaneously and analyse the effect of carbon storage on the optimal choice between them. We show that higher stand density, long rotations and a possible switch to continuous cover management, with an emphasis on harvesting large trees with a high sawlog ratio, are the economically efficient carbon abatement methods in stand management. Optimal regime shifts between rotation forestry and continuous cover forestry in size-structured stands have not previously been addressed in the carbon storage literature. The importance

[4] Goetz et al. (2010) present even lower cost ranges for uneven-aged forestry in Spain, especially if soil carbon is taken into account.

of our results is further emphasized by recent arguments that forest heterogeneity (age, size and species structure) may improve forest resilience under disturbances caused by climate change (Gamfeldt et al. 2015). The next step, then, will be to optimize carbon storage and wood production in mixed-species stands.

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Tables

Table 1. Size class -specific parameter values, per tree.

Size class	Diameter (cm)	Basal area (m^2)	Sawlog volume, SI = 15 (m^3)	Pulpwood volume, SI = 15 (m^3)
1	7.5	0.004	0.000	0.014
2	12.5	0.012	0.000	0.067
3	17.5	0.024	0.000	0.167
4	22.5	0.040	0.234	0.081
5	27.5	0.059	0.446	0.065
6	32.5	0.083	0.684	0.060
7	37.5	0.110	0.963	0.050
8	42.5	0.142	1.253	0.050
9	47.5	0.177	1.574	0.043
10	52.5	0.216	1.900	0.039
11	57.5	0.260	2.214	0.033
12	62.5	0.307	2.565	0.031

Table 2. Parameter values for the harvesting cost function.

i	C_{i0}	C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	C_{i7}
th	2.100	1.150	0.412	0.758	0.180	1.000	2.272	0.535
cl	2.100	1.000	0.397	0.758	0.180	1.000	1.376	0.393

Table 3. Effect of carbon pricing on optimal stand management, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price	Rotation age	Timing of first harvest	Harvest interval at steady state	Diameters of trees harvested at steady state	Mean stand volume
	(€ tCO_2^{-1})	(years)	(years from stand regeneration)	(years)	(cm)	(m^3 ha^{-1})
2%	0	130	45	–	–	138
	10	150	45	–	–	152
	20	170	50	–	–	174
	30	∞	50	25	32.5–52.5	182
	60	∞	50	20	37.5–52.5	224
4%	0	∞	40	20	22.5–37.5	68
	10	∞	45	25	22.5–42.5	79
	20	∞	45	20	27.5–42.5	114
	30	∞	50	20	32.5–47.5	169
	60	∞	55	25	37.5–57.5	234

Table 4. Effect of carbon pricing on timber production and carbon storage, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price	Rotation age	Mean annual sawlog / total yield	Mean CO_2 storage in living trees	Mean CO_2 storage in dead tree matter	Mean CO_2 storage in timber products	Discounted CO_2 sequestration
	(€ tCO_2^{-1})		(m^3 ha^{-1} a^{-1})	(tCO_2 ha^{-1})	(tCO_2 ha^{-1})	(tCO_2 ha^{-1})	(tCO_2 ha^{-1})
2%	0	130	6.3 / 7.6	207	53	80	198
	10	150	6.5 / 7.6	227	53	81	213
	20	170	6.7 / 7.6	260	54	83	232
	30	∞	5.7 / 6.0	271	43	69	244
	60	∞	5.7 / 6.0	335	44	70	269
4%	0	∞	3.8 / 4.5	101	30	48	108
	10	∞	4.0 / 4.7	118	32	51	115
	20	∞	5.0 / 5.6	170	38	62	123
	30	∞	5.7 / 6.1	252	43	70	133
	60	∞	5.6 / 5.8	349	43	67	144

Table 5. Forestry revenues, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price (€ tCO_2^{-1})	Discounted timber income (€ ha^{-1})	Discounted carbon subsidies (€ ha^{-1})	Net present value (€ ha^{-1})
2%	0	9 863	0	8 780
	10	9 791	2 128	10 865
	20	9 514	4 648	13 127
	30	9 174	7 314	15 488
	60	8 000	16 127	23 127
4%	0	2 662	0	1 662
	10	2 610	1 148	2 758
	20	2 483	2 462	3 945
	30	2 233	3 992	5 225
	60	1 726	8 666	9 392

Figure captions

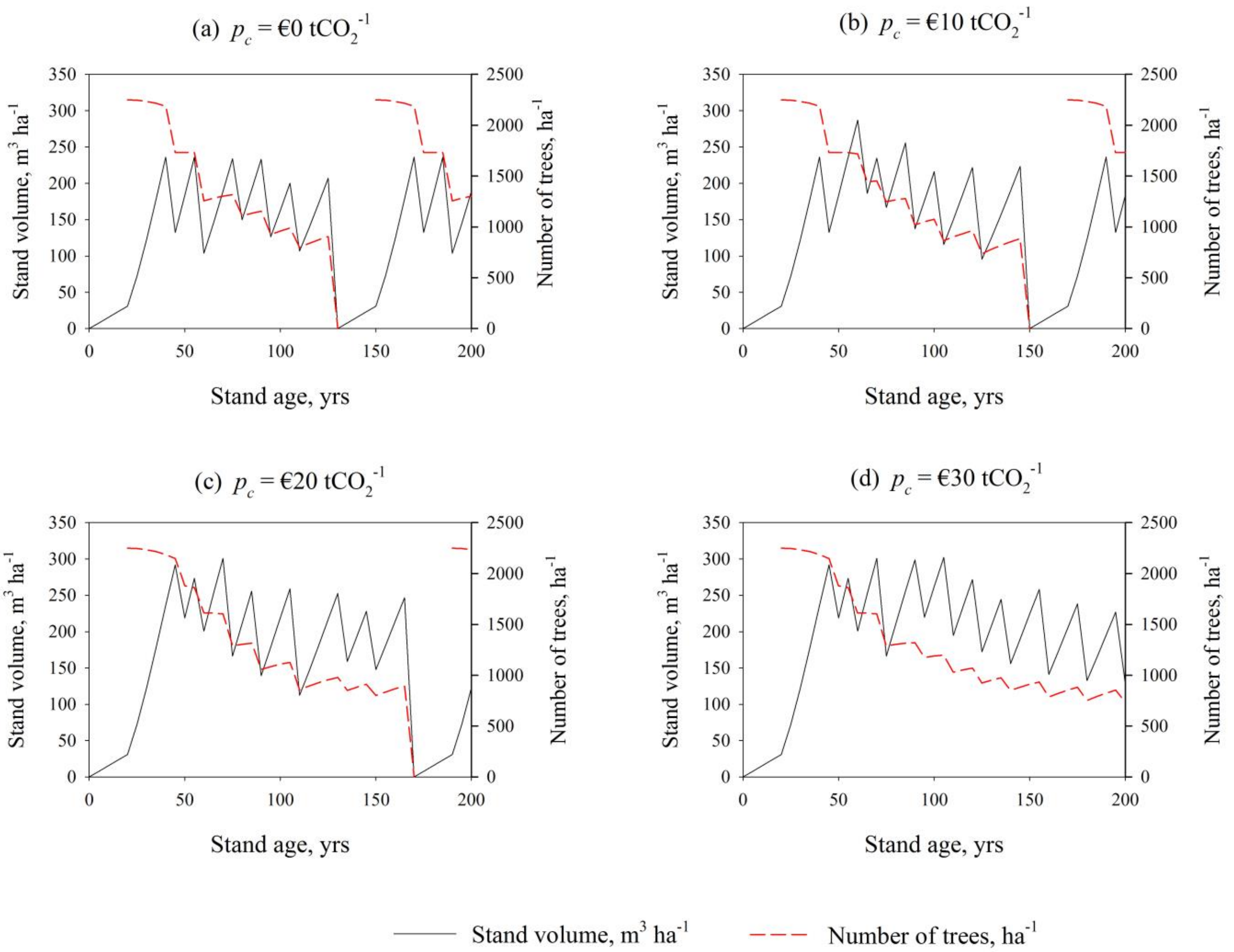
Figure 1. Stand volume and number of trees, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

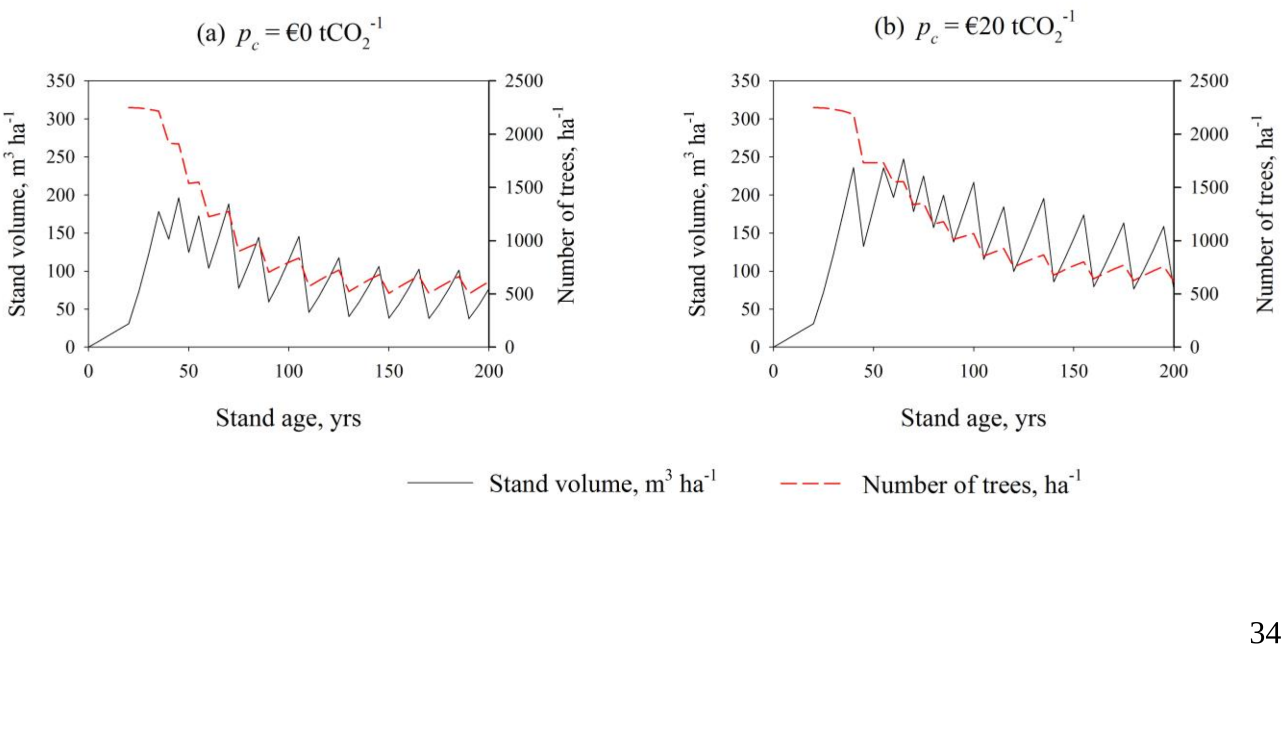
Figure 2. Stand volume and number of trees, with a 4% interest rate and carbon prices €0 and €20 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

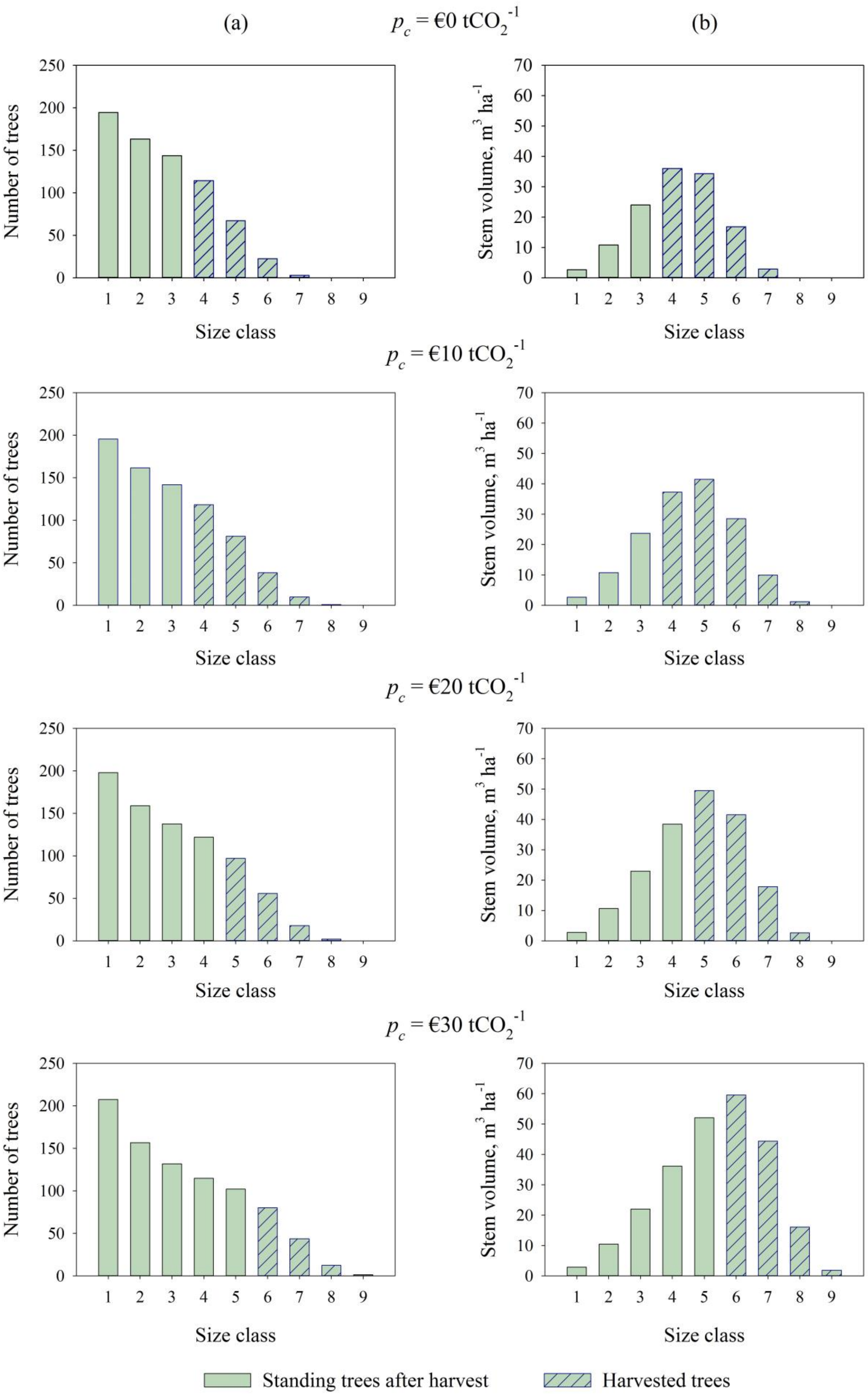
Figure 3. Optimal steady-state structures expressed as (a) number of trees and (b) commercial volume in each size class, with a 4% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Size classes begin from a diameter of 7.5 cm and increase in 5-cm intervals. Note: w = €1000 ha^{-1}.

Figure 4. Total carbon storage, including carbon storage in living trees, dead tree matter and timber products, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

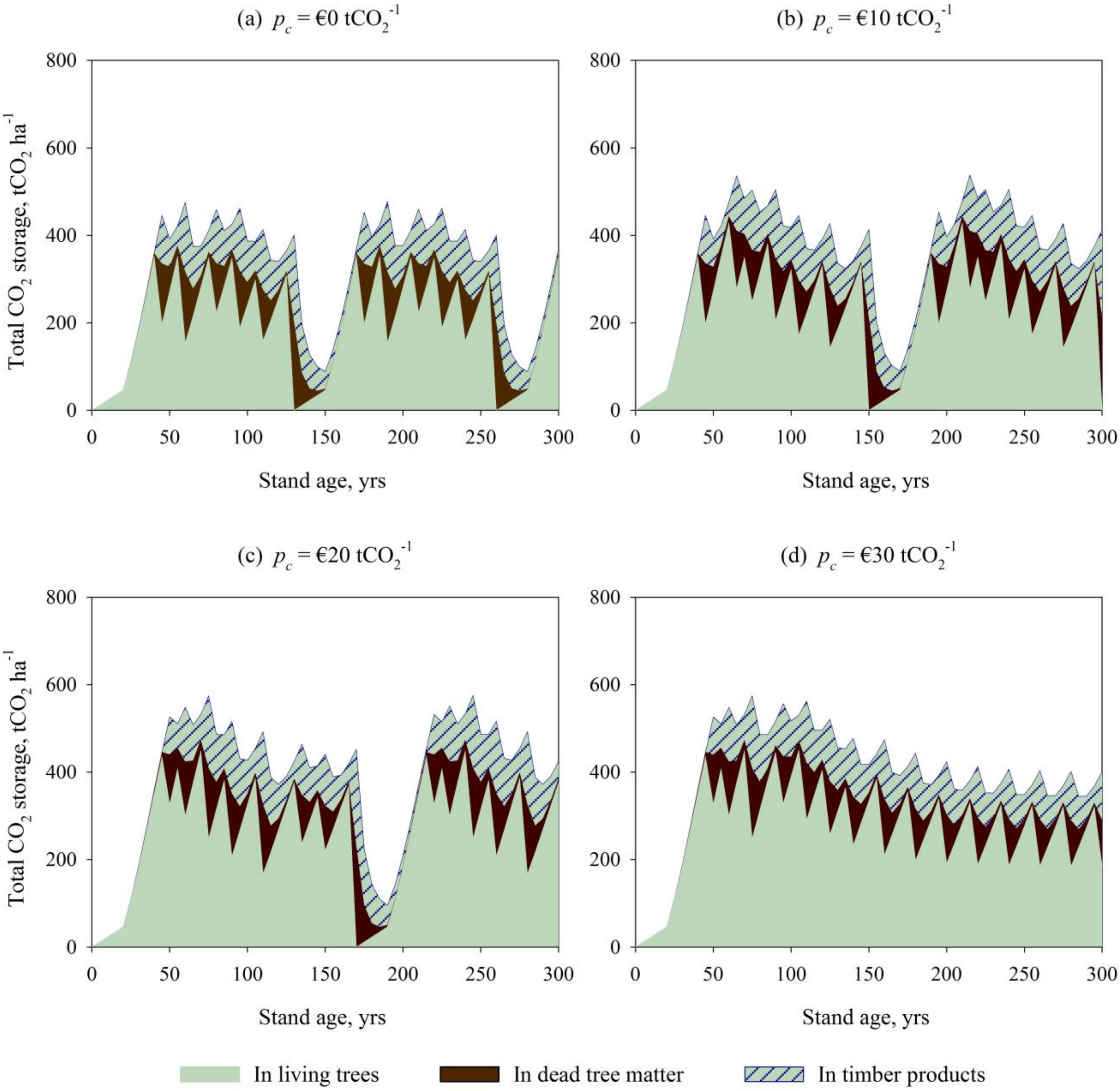
Figure 5. Marginal abatement costs. Note: w = €1000 ha^{-1}.

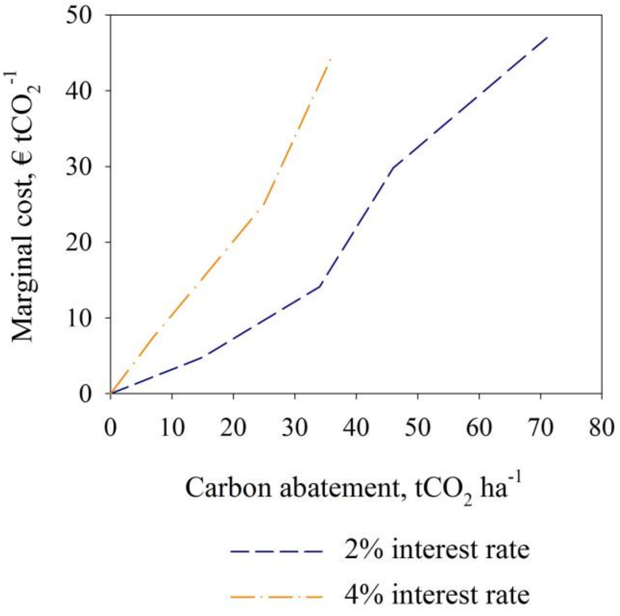

(a) p_c = €0 tCO_2^{-1}
(b) p_c = €10 tCO_2^{-1}
(c) p_c = €20 tCO_2^{-1}
(d) p_c = €30 tCO_2^{-1}
Stand volume, m^3 ha^{-1}
Number of trees, ha^{-1}
Stand age, yrs
Stand volume, m^3 ha^{-1}
Number of trees, ha^{-1}


(a) p_c = €0 tCO_2^{-1}
(b) p_c = €20 tCO_2^{-1}
Stand volume, m^3 ha^{-1}
Number of trees, ha^{-1}
Stand age, yrs
Stand volume, m^3 ha^{-1}
Number of trees, ha^{-1}



(a)
p_c = €0 tCO_2^{-1}
(b)
p_c = €10 tCO_2^{-1}
p_c = €20 tCO_2^{-1}
p_c = €30 tCO_2^{-1}
Number of trees
Stem volume, m^3 ha^{-1}
Size class
Standing trees after harvest
Harvested trees


(a) p_c = €0 tCO_2^{-1}
(b) p_c = €10 tCO_2^{-1}
(c) p_c = €20 tCO_2^{-1}
(d) p_c = €30 tCO_2^{-1}
Total CO_2 storage, tCO_2 ha^{-1}
Stand age, yrs
0
200
400
600
800
0
50
100
150
200
250
300
In living trees
In dead tree matter
In timber products


50
40
30
20
10
0
Marginal cost, € tCO2-1
0 10 20 30 40 50 60 70 80
Carbon abatement, tCO2 ha-1
2% interest rate
4% interest rate